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DEVELOPMENT OF A SPIRAL DEVICE FOR MEASURING THE SOLIDS FLOW IN A CIRCULATING FLUIDIZED BED

J. Christopher Ludlow[1], Larry Lawson[1], Larry Shadle[1], Madhava Syamlal[2],
[1]National Energy Technology Laboratory
PO Box 880, Morgantown, WV 26507-0880
[2]Fluent, Inc.
3647 Collins Ferry Road, Suite A
Morgantown, WV 26505

Abstract - The solids circulation rate within the cold flow circulating fluidized bed test facility at the National Energy Technology Laboratory is being measured using a twisted vane flow meter. The meter consists of a vertical twisted vane inserted into the packed bed portion of the standpipe. The solids downward flow causes the vane to rotate, and from the rate of rotation the solids velocity is calculated. This velocity combined with the cross sectional area of the standpipe and the bulk density of the circulating material allows the overall circulation rate to be determined. Circulation rates as high as 45,000 kg/h have been measured for coke breeze bed material. An advantage of the spiral device is that the solids flow rate is measured continuously. A disadvantage is that the measurement becomes unreliable in the rare occasions when the standpipe starts to bubble.

Introduction

The National Energy Technology Laboratory has built a circulating fluidized bed (CFB) test facility is designed to operate at ambient temperature and at pressures up to 345 kPa (50 psia). The facility was constructed so that research in different CFB operating regimes, as well as performance characterization for different parts of the unit, could be pursued. To achieve these research goals, the unit is instrumented with 55 differential pressure transmitters, 10 air flow loops, and various pieces of non-traditional instrumentation. One of these non-traditional instruments is a fiberglass twisted vane solids flow meter. This twisted vane flow meter, or as we have come to call it, the Spiral, is placed along the centerline of the standpipe or downcomer in the packed bed region and continuously measures the solids circulation rate.

Background

Solids circulation rate typically is one of the fundamental quantities of interest in CFB research. As such, circulating fluidized bed researchers have reported a variety of methods for determining the solids circulation rate. To measure the circulation rate using a solids flow interruption technique (Brereton, and Grace, 1993; Hyppanen et al., 1993; Bodelin et al., 1993), typically, a porous valve is closed someplace in the standpipe or downcomer section of the unit and solids accumulation or depletion above or below the valve is noted. This accumulation or depletion might be measured by noting the change in bed height at some location within the bed, measuring the change in pressure drop across the changing bed, or measuring the weight of accumulated solids in a section of the bed. By noting the bed height change as a function of time along with bed bulk density, the overall circulation rate can be calculated. Others track particles in the packed bed portion of the standpipes to measure the particle velocity (Bierl et al., 1980, Burkell et al., 1993, Kuramoto et al., 1986). These tracer particles might haved a differently colored or fluorescent for optical tracking, or have some other unusual property such as ferromagnetism which allows their monitoring. Circulation rate is determined by noting the tracer particle's velocity down the standpipe and assuming a solids bulk density. Both the particle tracking and the flow interruption technique give only an instantaneous value of solids velocity and depending on the details of their implementation, can be relatively disruptive to the process.

Other researchers have devised continuous techniques for the determination of circulation rate. Liu and Huan (Liu and Huan, 1995) use the rotation of a small multiblade turbine to measure solids velocity within the standpipe. While having the distinct advantage of being a continuous measurement, the constant pitch of the blades is somewhat disruptive of the solids flow past the turbine. Another continuous measurement technique is reported by Davies and Harris (Davies and Harris, 1992) which uses solids flow through a slot to estimate solids flow. For this technique, solids flow into a container with one of more slots cut into the sides of the container. As the solids flow into the container, the amount of material increases until the flow out through the slots equals the flow in. By weighing the amount of material in the container, the solids flow rate into the container can be calculated. As with the "snap shot" techniques above, these continuous techniques can be somewhat disruptive of the process.

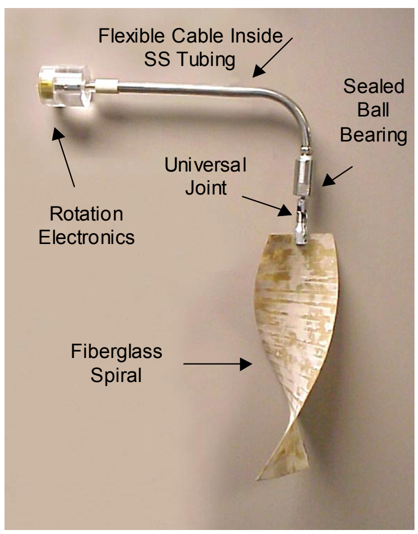
General CFB Layout

The NETL circulating fluid bed facility (Monazam et al., 2001) is configured with a 15.45 m (50.5 foot) tall, 0.305 m (12 inch) inside diameter riser and a 0.253 m I.D. (10 inch) standpipe. Solids and gas exiting from the side at the top of the riser pass through a 0.203 m (8 inch) I.D. pipe before entering the primary cyclone. Solids from the primary cyclone fall directly into the standpipe while gas and entrained solids pass through a secondary cyclone before exiting to the bag house. Solids captured by the secondary cyclone are reintroduced into the standpipe at the 6.34 m level. At the bottom of the standpipe is a 0.254 m I.D. non-mechanical valve used to control the flow of solids back into the riser. To date, three different configurations for the non-mechanical valve, a AJ@ valve, an AL@ valve, and a loop seal have been used.

Instrumentation and controls are attached to the circulating loop to attain pressure balance, solids fluidization and transport. The maximum riser air flow rate is nominally 3,400 standard cubic meters per hour (120,000 SCFH) or about 12.9 m/s superficial gas velocity in the riser. Fluidization air is supplied to the non-mechanical valve at various locations depending on the type of valve being used. The lower standpipe aeration flow, or AMove-Air@, is delivered to two coplanar nozzles at the 0.46 m elevation level in the standpipe. This Move-Air is used as the primary control for solids circulation rate and has a maximum value of slightly over 11.3 SCMH (400 SCFH). Additional standpipe aeration flows are provided at the 2.1 m (7 ft.), 4.6 m (15 ft.), 6.4 m (21 ft) and 8.5 m (28 ft) elevations. Appropriate aeration flows are determined during scoping studies to provide smooth solids flow with evenly distributed pressure gain along the length of the standpipe.

The Twisted Vane Solids Flow Meter – the Spiral

The solids circulation rate is measured in the standpipe through the use of a fiberglass twisted vane flow meter. While the concept for this instrument is not new (Danatos and Schall, 1961), there do not seem to any commercial offerings. The flow meter consists of two basic parts, 1) the twisted vane and 2) electronics used to detect the rotation of the vane. This twisted vane, or Spiral, is 0.140 m (5.5 in.) wide, 0.305 m (12.25 in) long, and is shaped so that there is nominally 180 degrees of twist over the length of the vane (see Figure 1.) Installation of the Spiral (also shown in Figure 1) is such that the fiberglass vane hangs down along the centerline of the standpipe while the electronics measuring vane rotation remain outside the vessel.



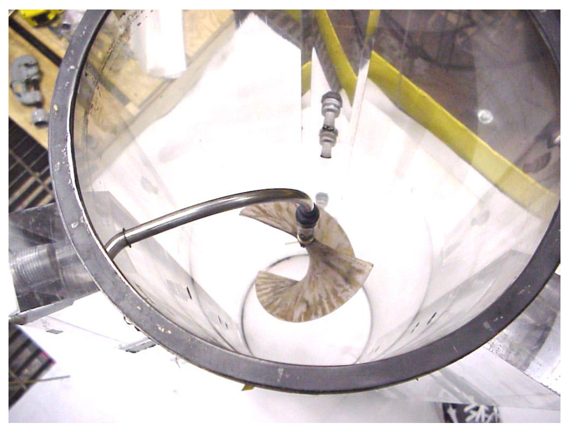


Figure 1. Fiberglass Spiral and Top View of Typical Installation

Since the vane is installed in the packed bed region of the standpipe, solids movement past the Spiral causes the twisted vane to rotate. The twist of the Spiral is such that solids move straight down the standpipe and are not significantly displaced by the motion of the Spiral. The electronics used to measure the vane=s rotation consist of a commercially available two channel quadrature encoder which produces two channels or sets of electrical pulses as its input shaft rotates. Pulses of one channel are offset from those of the other channel by 90 degrees. The frequency of these pulses is a linear function of the speed at which the input shaft rotates. There are 32 pulses per channel for 360 degrees of shaft rotation. Considering both channels together, there are 128 different states for the electrical outputs which we monitor to determine rotational speed. Thus we are able to detect about 2.8 degrees of shaft rotation. Rotating motion of the Spiral is mechanically transmitted to the encoder, which is located outside of the standpipe, by means of a flexible cable. Bed solids are prevented from entering this flexible cable enclosure by means of a sealed ball baring located at the end of the cable. Electrical pulses produced by the encoder are fed to a small stand-alone computer which detects the 128 different electrical states and converts the frequency at which these states change to an analog signal which is then recorded by the data logging hardware.

Calibration and Sensitivity

Calibration of the Spiral involves determination of the actual vane rotation for a given standpipe bed movement. This is achieved at the NETL facility by closing a gate valve installed midway up the standpipe. Closing this valve while the bed is circulating, interrupts the solids flow and allows the decreasing bed height below the valve to be monitored through the transparent standpipe wall. Bed height and Spiral output can then be recorded and graphed. Such an experiment was conducted in three different trials and has been plotted in Figure 2.

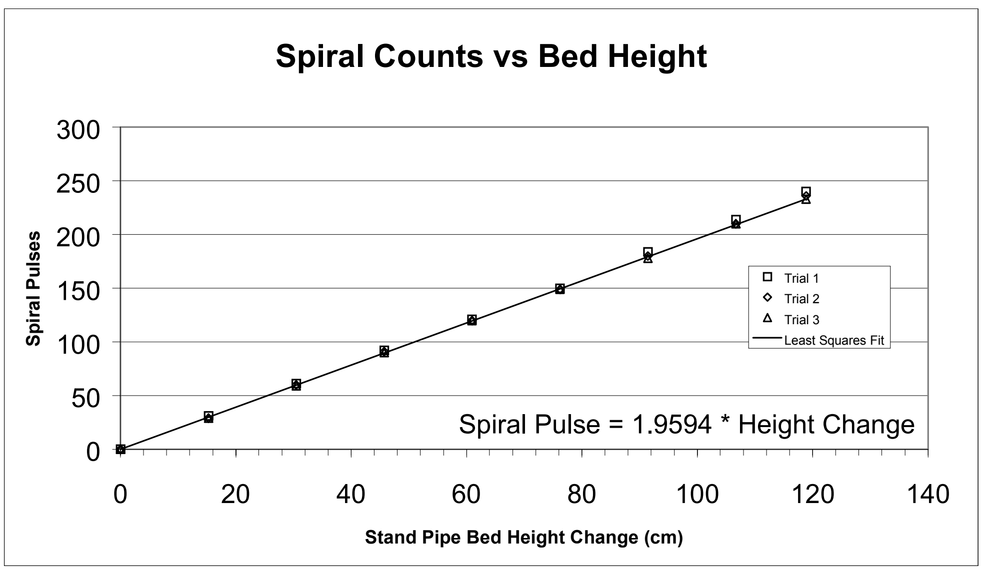


Figure 2. Determination of Spiral output for measured standpipe bed movement.

The slope of the resulting line in Figure 2 is the vane's pitch, 195.9 pulses/meter (1.959 pulses/cm), and is used to relate the solids circulation rate to the frequency of electrical pulses produced by the Spiral according to:

$$M = \frac{\left(3600 * A_{sp} * \omega * \rho_s\right)}{Pitch_{vane}} \quad (1)$$

From Equation (1), it can be seen that the resolution of the frequency measurement is a significant factor in the resolution of the circulation rate measurement. A resolution of 1 Hz in the pulse frequency (T), results in a resolution in the kilograms per hour solids flow rate of approximately 93.1% the numerical value of the bulk density. For example, the cork material NETL most recently used has a bulk density of 88.1 kg/m^3. With a 1 Hz frequency resolution, there is an 82.0 kg/h resolution (93.1% of 88.1) in the measured circulation rate. Certainly, as the resolution of the frequency measurement increases, so does the resolution of the solids flow measurement. A resolution of 0.1 Hz corresponds to a solids flow resolution of 8.2 kg/h.

Because of the relatively low weight of the Spiral, changes in the solids velocity quickly result in changes in the rotational speed of the Spiral. For practical purposes, the transient response of the device is limited only to the time interval over which the frequency of encoder pulsation is measured. Because of the digital nature of the encoder pulsation (there either is a pulse or there is not), low frequency measurement capability entails the counting of pulses over relatively long periods of time. To measure a frequency of 0.1 Hz, one would need to measure one pulse during a period of 10 seconds. Solids velocity changes that might occur during that interval would be averaged over that time. Hence, resolution of the circulation rate for short time intervals implies a larger minimum circulation rate measurable.

Implicit in the use of the bulk density in Equation (1) is the assumption that the measured density value determined in the lab is the same at that value within the standpipe and that it does not change as solids circulate. We have convinced ourselves that this assumption is reasonably justified by modeling the steady state void fraction profile of the standpipe as a function of gas aeration flows, measured circulation rate, and standpipe pressure profile. This model suggests that the void fraction of solids around the Spiral does not grossly change until the standpipe bed is almost fluidized.

The Spiral in Use

Perhaps the most noticeable advantage of the Spiral over more traditional solids flow measurement techniques is the fact that the Spiral results in a continuous measurement. Figure 4 shows a three minute segment of Spiral data, taken every 2 seconds. For these data, the bed material was the ground cork mentioned above and all process variables such as riser air flow and aeration flows were held constant. Because of the continuous nature of the measurement, it is easy to see that the flow of solids down the standpipe (and into the riser) is not constant, but actually speeds up and slows down during normal operation. Because of this stick-slip behavior, the solids circulation rate significantly changes from a value close to 1,000 kg/h at 15 seconds to 570 kg/h at 36 seconds. This magnitude of change is in fact modest compared to the 4,500 kg/h to 9,000 kg/h fluctuations over a 4 second interval experienced with other denser bed materials.

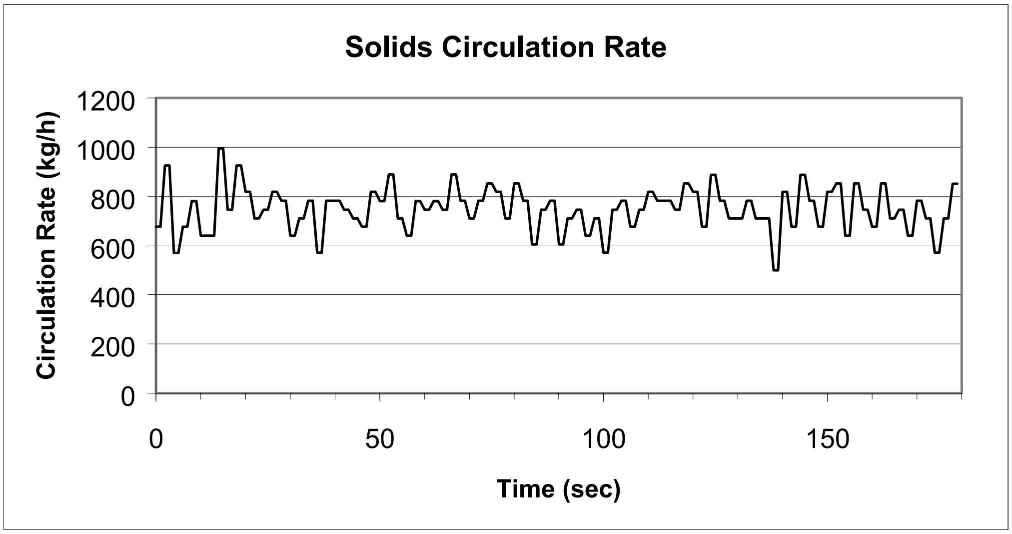


Figure 4. Instantaneous Circulation Rate as a Function of Time.

The continuous nature of the Spiral output has also allowed us to begin looking at the time dependant response of the circulating fluid bed with non-constant standpipe aeration flows. Figure 5 shows the measured circulation rate in response to a sinusoidal move air flow. It is easy to see that as the aeration flow varies the solids circulation rate changes with the same period as the aeration flow, and that there is very little time delay between the two flows. Additionally, it can be seen that these relationships do not change significantly when the period of sinusoidal air flow changes from 90 seconds to 180 seconds. The ability to measure circulation rate continuously has allowed us to begin to investigate the transient response of the CFB system in general and specifically the standpipe and riser to sinusoidally varying circulation rates. Preliminary results indicate that the pressure drop across the riser demonstrates a measurable time delay from the circulation rate, and that the amplitude of the riser's pressure fluctuations decrease as the frequency of the circulation rate variation increases.

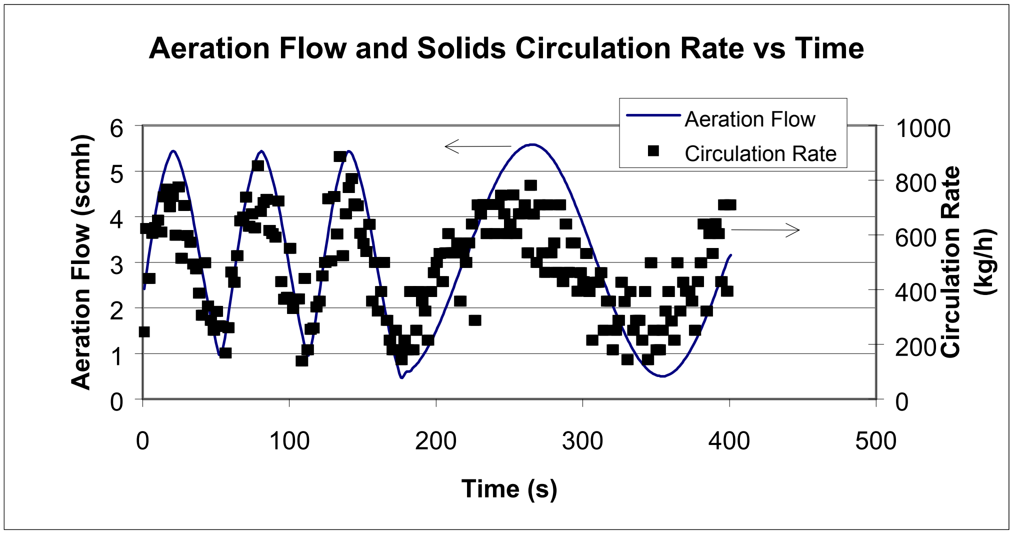


Figure 5. Solids Circulation Rate with Sinusoidal Aeration Flow

Conclusions

The measurement of the solids circulation rate is typically one of the fundamental quantities of interest in CFB research. Most of the techniques used to measure the circulation rate measure that rate over a relatively short period of time and because of the variability of circulation rate, may not accurately represent the average solids flow. Additionally, depending on implementation, some of these techniques can be relatively disruptive. The twisted vane solids flow meter used at NETL is a device that allows continuous measurement and recording of the solids circulation. Design of the Spiral is such that solids are not significantly displaced as they move past the twisted vane. With the Spiral, we have been able to measure solids circulation rate variability due to stick-slip flow within the standpipe and are beginning experiments where the solids flow varies sinusoidally. Continuous recording of solids flow with other CFB process variables opens up the opportunity of subsequent time dependant analysis of circulation rate and CFB operation

Nomenclature

A_{sp} = Cross sectional area of standpipe [m^2]
M = Mass Flow [kg/h]
$Pitch_{vane}$ = Pitch of the twisted vane [pulse/m]

Greek Symbols
T = Frequency of encoder pulsation [pulses/s]
D_s = Bed solids bulk density [kg/m^3]

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